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Abstract: The paper aims to offer a user-centred methodological framework to guide design and evaluation of applications combining Brain-Computer Interface (BCI) and Virtual Environment (VE). Our framework is based on the contributions of ergonomics to ensure these applications are well suited for end-users. It provides methods, criteria and metrics to perform the phases of the human-centred design process aiming to understand the context of use, specify the user needs and evaluate the solutions in order to define design choices. Several ergonomic methods (*e.g.*, interviews, longitudinal studies, user based testing), objective metrics (*e.g.*, task success, number of errors) and subjective metrics (*e.g.*, mark assigned to an item) are suggested to define and measure the usefulness, usability, acceptability, hedonic qualities, appealingness, emotions related to user experience, immersion and presence to be respected. The benefits and contributions of our user centred framework for the ergonomic design of applications combining BCI and VE are discussed.

Key-words: Brain-Computer Interface; Virtual Environment; Virtual Reality; Ergonomics; User-Centred Design; Evaluation

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Résumé : Ce rapport présente un cadre méthodologique centré sur l'utilisateur visant à assister la conception et l'évaluation d'applications combinant les Interfaces Cerveau-Ordinateur (ICO) et les Environnements Virtuels (EV) afin qu'elles soient adaptées aux utilisateurs finaux. Sur la base de connaissances issues de l'ergonomie, ce cadre fournit des méthodes, des critères et des métriques permettant de réaliser les étapes du processus de conception centrée-utilisateur, étapes visant à comprendre le contexte d'utilisation, spécifier les besoins des utilisateurs et évaluer les solutions développées. En l'occurrence, plusieurs méthodes ergonomiques (e.g., entretiens, études longitudinales, évaluations avec des utilisateurs), métriques objectifs (e.g., réussite de la tâche, nombre d'erreurs) et métriques subjectifs (e.g., note associée à un item) sont suggérés pour définir et mesurer l'utilité, l'utilisabilité, l'acceptabilité, les qualités hédoniques et affectives, l'expérience utilisateur, l'immersion et la présence associées à l'interaction avec ces applications. Les bénéfices et les contributions de notre cadre méthodologique pour la conception ergonomique des applications combinant ICO et EV sont ensuite discutés.

Mots clés : Interface Cerveau-Ordinateur; Environnement Virtuel; Réalité Virtuelle; Ergonomie; Conception Centrée-Utilisateur; Evaluation

1. Introduction

A virtual reality system is "an immersive system that provides the user with a sense of presence (the feeling of 'being there' in the virtual world) by means of plausible interactions with a synthetic 3D environment simulated in real-time" [1]. A virtual reality application is composed of display devices for information presentation (e.g., for visual feedback, proprioceptive or cutaneous feedback, sound feedback), interaction devices (e.g., motion capture devices, audio input devices, Brain-Computer Interface), and a virtual environment. This virtual environment is composed of 3D entities (i.e., 3D objects, virtual agents) which are simulated in real time and change according to the user's actions.

Most applications combining Brain Computer-Interface (BCI) and Virtual Environments (VE) mainly consist of using the BCI as an input device to interact with the VE providing the user with a way to interact with the VE solely by means of brain activity and using the available output devices (mainly visual feedback) to provide a meaningful feedback to the user [2]. Today, getting these applications out of the laboratories, and designing and evaluating them for concrete applications seems a challenging task [3]. To do so, two complementary approaches have been proposed: a technocentric design and an anthropocentric design.

The technocentric orientation aims to design and optimize an innovative application by testing its technological possibilities and solving technical challenges [4]. This research path hardly considers the characteristics of human activity. Typically, these studies aim to improve the performance[3] of the BCI in terms of information transfer rate [5], classification accuracy and error rates in the detection of mental states. More recently, some studies have dealt with Hybrid Brain-Computer Interfaces [6] which can be defined as a combined use of two BCIs or at least one BCI with another system. This additional system can be either a brain signals (e.g., Motor Imagery, SSVEP, P300) or other kind of input device (e.g., Electrooculography, Electrocardiography, Electromyography, Electro dermal Activity Sensor).

Conversely, the anthropocentric orientation aims to design an application which will be used by end-users. This approach focuses on the characteristics, capabilities and resources of end-users, the context of the use of the designed applications and the users' activity [7]. In the anthropocentric orientation, studies of applications combining BCI and VE focus on user-centred design (e.g. [8]), user experience (e.g. [9]) and usability of the BCI device (e.g., [10]). This anthropocentric approach is rarely used in the design and evaluation of applications combining BCI and VE. Indeed, the involvement of real end-users in the design process exists (e.g., [11, 12]) but it is not common. The evaluations are mainly performed in laboratories and not in field conditions [3]. The designed applications are often video games only developed for experimentation and not to meet an industrial need (e.g., [13]). One reason could be the absence of a methodological framework dealing with the ergonomic design of applications combining BCI and VE, compared to the research conducted in technocentric design. However, some authors like [13] and [14] have conducted relevant studies of user-centred design methodology. In his thesis, Gürkök compared the user experience resulting from the interaction between a BCI on the one hand and, on the other hand, that produced during an interaction with another control device [13]. To carry out this comparison they suggested a new approach called "Equalised Comparative Evaluation". Plass-Oude Bos and al. [14] adapt the usability characteristics commonly used in human-computer interaction (i.e., learnability, memorability, efficiency, effectiveness, error handling, and satisfaction) to the

[3] Please see [132] for a quasi-exhaustive state of the art on evaluation criteria of performance.

BCI games. Moreover, they describe their own work including the comparison of the user experience in a computer game as a function of the devices (e.g., BCI control versus others devices like a keyboard) and paradigms (e.g., imaginary versus actual movements) and the suggestion of methods for estimating the user state in order to lead to affect-based games adaptation. In summary, this research focuses on a specific field of application of the BCI (i.e., video games) and aims to improve the human-computer interaction in terms of user experience and usability.

The purpose of this paper is to propose a user-centred methodological framework to guide design and evaluation of applications combining BCI and VE, on the basis of the contribution of ergonomics. This methodological framework deals with the ergonomic design of these applications and suggests methods, criteria and metrics. Our framework intends to be generic and, to do so, it integrates others ergonomic criteria (e.g., usefulness and acceptability) and their evaluation metrics, in addition to user experience and usability. It intends to be applicable to various VE-based systems and applications such as therapeutic tools, support for dialogue, etc. and not be specific to games

The remainder of this article is organized as follows. In the second section we provide an overview of empirical studies, mainly technocentric, concerning the applications combining BCI and VE In the third section, the user-centred design is particularly suited to applications combining BCI and VE, compared to other design models used in ergonomics which are more difficult to apply in the context of emerging technologies. In the fourth section, the importance of using several ergonomic methods in the context of user-centred design is explained. In the fifth section, we highlight eight ergonomic criteria to be respected to ensure that applications combining BCI and VE are suited for end-users. In the sixth section, for each criterion, the metrics used in empirical studies on design and evaluation of applications combining BCI and VE are identified. In the seventh section, the contribution of our methodological framework to the ergonomic design of applications BCI/VE is discussed and some research perspectives are provided.

2. Empirical studies on applications combining BCI and VE

This section aims to provide an overview on the empirical studies which have already been realized in the context of VE and BCI based tools.

2.1 Methodology used to select papers

The digital library Scopus which, according to [13], covers 97.33% of articles about the BCI research field was used. Articles written between 1973 (first BCIs appeared) and 2012 were considered. Only journal and conference articles were considered, and review, survey and other articles potentially not reporting a specific study with participants were excluded. Press articles and articles not written in English were excluded. The search was done in the title, abstract and keyword fields of articles. The following keywords were included: “brain computer interface” AND “virtual environment” AND “evaluation”. Consequently, on January 31st 2013, the following query on Scopus was issued:

TITLE-ABS-KEY(("brain computer interface" OR bci OR eeg OR nirs) AND ("virtual environment" OR ve OR "virtual reality" OR vr) AND (evaluation OR assessment OR experiment)) AND DOCTYPE(ar OR cp) AND PUBYEAR > 1972 AND PUBYEAR < 2013 AND (LIMIT-TO(LANGUAGE, "English"))

167 papers were found. 1 duplicate article, 8 papers without empirical studies (e.g., states of the art), 37 noises (e.g., papers in which VR refers to "vasoreactivity"), 2 empirical studies which did not involve human subjects (e.g., but monkeys) and 4 papers for which we did not have access to the full text were removed. At the end of all the exclusions, 115 papers were considered. These were articles describing studies dealing with the evaluation of brain computer interface used in virtual reality. Among these papers, 60 papers dealing with the BCI as a measurement tool of brain activity during the execution of a task in a VE (known as ElectroEncephaloGraphy) have not been taken into account. ElectroEncephaloGraphy Spectrum Analysis can be used:

- to study the neurophysiological age differences during task-performance in a stereoscopic VE [15],
- to measure the loss of consciousness in epilepsy using virtual reality driving simulation and other video games [16],
- to understand a human driver's behaviour in demanding situations [17],
- to measure stress induced during a bomb explosion simulation [18],
- to analyse possible differences in the brain activity of subjects during the viewing of monoscopic or stereoscopic contents [19],
- to investigate motion-sickness-related brain responses using a VR-based driving simulator on a motion platform with six degrees of freedom which provides both visual and vestibular stimulation to induce motion sickness in a manner that is close to that in daily life [20],
- to prove that the encoding of visual-spatial information in working memory requires more cerebral efforts than retrieval [21],
- to investigate the characteristic changes in the physiology of cyber sickness when subjects were exposed to virtual reality [22].

The following analyses are focused on the remaining 55 papers concerning the BCI as an input device to interact with a VE.

2.2 Results: characteristics of empirical studies on BCI as an input device to interact with a VE

2.2.1 Limited number of participants

Evaluations of applications combining BCI and VE involved 10 participants on average (min=1; max=100). Relatively this low number of participants indicates that there is little chance that the participants involved are representative of the entire population which is heterogeneous in terms of age, gender, expertise level in VR, expertise level in BCI, etc. So, it is difficult to identify the individual factors which probably impact on some dimensions of the human-virtual environment interaction based-BCI (e.g., performance). In a study, [23] aim to assess the influence of flickering stimuli (necessary to elicit SSVEP in brain activity) integrated into a virtual scene on navigation performance and subjective preference with seventeen participants (14 men and 3 women) aged from 21 to 35 where all had normal or corrected-to-normal vision. With more participants, it could be interesting to create several experimental groups of (at least) five participants each as recommended by Nielsen: e.g., one group composed of men with normal vision and aged 20, a second group composed of men with corrected vision and aged 20, a third group composed of women with normal vision and aged 20, a fourth group composed of women with corrected vision and aged 20, a fifth group composed of men with normal vision and aged 40, a sixth group composed of men with corrected vision and aged 40, a seventh group composed of women with normal vision and aged 40, an eight group composed of women with corrected vision and aged 40. Thus, the effect of gender, eye level and age on navigation performance with flickering stimuli integrated in a virtual environment could be investigated.

Another problem in these studies is that the participants involved are rarely the end-users of these applications. For example, [24] and [25] evaluated a BCI - VR neurorehabilitation system with healthy participants, but people with disabilities due to a stroke could have other results in terms of classification accuracy and satisfaction during their VE interaction-based BCI. However, some studies involved actual end-users. For example, [26] involved U.S. Army sergeants to study commander task performance under varying task load conditions during team operations in a complex army-relevant virtual environment; [27] demonstrated that a tetraplegic subject, sitting in a wheelchair, could control his movements in a VE by the use of a self-paced (asynchronous) BCI based on one single EEG recording; [28] involved a tetraplegic subject to test an alternative spelling device called " Virtual Keyboard" (VK) based on the Graz-BCI, and [29] involved subjects with Attention Deficit Hyperactivity Disorder treatment (ADHD) to test the feasibility and usefulness of this system based on neuro-feedback and virtual reality technology for ADHD. These studies, even if few, suggest that it is possible to integrate end-users in the design and evaluation of these very emerging technologies and that the designers of BCI-based systems are concerned with the characteristics and needs of real end-users.

Finally, it seems that the users are mainly involved in user tests without interviews or questionnaires after the interaction with application (i.e., 46/55 papers). The objective was to collect objective measures (e.g., time for task accomplishment) and not subjective measures (e.g., satisfaction on comfort). A risk here is achieving improvements in the systems that are not consistent with the characteristics and the needs of users.

2.2.2 Empirical studies focused on usability of BCI

The majority of empirical studies on a BCI as an input device to interact with a VE concern the usability criteria (Figure 1).

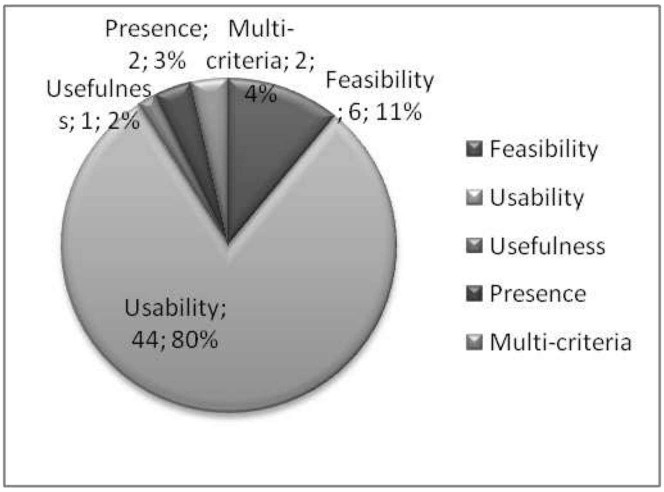

Figure 1. Criteria used to evaluate applications combining BCI and VE. For each criterion, number of papers concerned (n) and percentage (%) are specified.

The majority deal with usability in terms of classification accuracy, task success, time and satisfaction (Table 1).

Table 1. Overview of usability metrics used in BCI and VE papers.

Metrics	References
Classification accuracy[4]	[25, 26, 28, 92, 93, 94, 95, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112,113, 114, 115, 116, 117]
Task success	[27]
Satisfaction	[54, 118]
Classification accuracy and Time	[114, 119, 120]
Task success and Time	[96, 121, 122]
Task success and Satisfaction	[123]
Classification accuracy, Time and Task success	[63, 64, 65]
Task success, Time and	[124]

[4] According to [106], the BCI classification accuracy is a parameter, indicating how well the two brain states could be identified in each run. A classification accuracy of 100% denotes a perfect separation between the mental tasks (right hand movement imagination and foot movement imagination).

Satisfaction	
Task success, Classification accuracy and Satisfaction	[76]

These usability metrics help to ensure that applications run properly; they could be extended to other criteria (feasibility, presence, usefulness, presence and user experience) provided from literature on applications combining BCI and VE as in Table 2.

Table 2. Papers for feasibility, presence, usefulness and user experience.

Criteria	References
Feasibility	[111, 125, 126, 127, 128, 129]
Presence	[130, 131]
Usefulness	[29]
Usability and presence	[23]
Usability and user experience	[24]

This overview suggests that the majority of empirical studies evaluate the performance of applications combining BCI and VE. This suggests that the technocentric orientation remains dominant. However, anthropocentric orientation used in ergonomics could be relevant for designing applications more adapted to end-users in terms of usefulness, usability, hedonic quality and user experience. In the next section, the design models promoting this orientation are discussed. In the following sections, the papers that best illustrate the design models, ergonomic methods, ergonomic criteria and metrics that we develop in our methodological framework are detailed. These papers are part of the 55 papers and previous research on more specific dimensions (e.g., user experience in game-based BCI speller based-BCI).

3. Design models used in ergonomics

Designing emerging technologies-based applications suited to end-users requires design models used or advocated in ergonomic literature. These models have in common the promotion of an anthropocentric design involving users in the design process from the preliminary phases to actual use in order to integrate their characteristics and needs. After describing the limits of the "participatory design" model for emerging technologies, we emphasise that the "user-centred design" model - already in use for applications combining BCI and VE within a "computer-human interaction" perspective - is particularly promising for ergonomic design of these emerging technologies.

3.1 Participatory design

Participatory design approaches [30] seek to fully involve users in the process as co-designers by empowering them to put forward and generate design alternatives themselves and require the active participation of the users.

Participatory design is characterized by:

- A democratic [31] or multilateral participation in a design project [32] by all stakeholders including users,
- A strong end-users' implication in the decision making concerning the definition [33] and the transformation of the artefact [34],
- A developmental approach [35] which concerns the understanding of tasks and activities produced during the use of artefacts, and the evolution of users' skills depending on their appropriation of the artefacts [36].

According to [37], participatory design is interesting for the design of emerging technologies because the knowledge of the purpose of the artefact is not mandatory. Indeed, emerging technologies are characterised by unclear and undefined uses, which explain why participatory design is not easily implemented in design projects [38]. This is confirmed by the fact that we have not found applications combining BCI and VE designed in a participatory way. Four reasons could explain this observation:

- Participatory design does not have a clear process [39],
- It is difficult for designers to accept that stakeholders without a technical background (e.g., user) can impact the design [40]. Designers consider that users' feedbacks at the end of design process or during use are very difficult to implement,
- End-users' involvement in decision making is often limited, specifically in industrial projects, because they are not allowed to acquire sufficient knowledge to be able to make decisions,
- The principle of multilateral participation by all stakeholders is complex to implement [41] because it is difficult for designers to understand the user's activity and for users to know the technical constraints.

3.2 User-centred design

The user-centred design approaches focused primarily on activities and processes taking place at the design period in the systems' development and during which designers generate solutions placing users mainly in a reactive role [42].

The term "user-centred design" is sometimes used in BCI literature to evoke a concept which is assessed empirically (i.e., evaluated by a user during the accomplishment of an experimental task), as opposed to a theoretical concept (e.g. [43]). In the context of an application combining BCI and VE, this term has been used in [8]. For example, one of their studies had two purposes:

- Evaluate users' preference for three mental tasks (inner speech, association, mental state) which are more adapted than traditional paradigms (e.g., Motor Imagery, P300, and Steady-State Visually Evoked Potentials) considered too slow, non-intuitive, cumbersome or just annoying,
- Measure the link between recognition performance and the preference of users.

To do that, fourteen participants participated in five experiments consisting of playing at World of Warcraft for two hours and for five weeks. They were divided in two groups:

- A "real-BCI" group: they controlled their shape shifting action with their mental tasks, at least insofar as the system could detect it,
- A "utopia-BCI" group: they pressed the button to shape shift when they decided for themselves whether they performed the mental task correctly (in this group, the BCI system with 100% detection performance was simulated).

After user test sessions, the participants filled out a user experience questionnaire. The results show that the users prefer the association tasks whereas the mental state seems to be disliked the most. It appears also that recognition performance has a strong influence on user preference. These types of studies, also called "user-centred design" which is part of a human-computer interaction perspective, aim to design BCI-based interactions integrating human characteristics (i.e., that concern the interaction activity). However, the term "user-centred design" has a slightly different meaning in ergonomics which is complementary to this human-computer interaction perspective. Indeed, for ergonomics, an application combining BCI and VE must be designed in order to be integrated into a complex activity in which this will be a means - among others - to help users to perform a task (e.g., a BCI/VE-based tool aiming to diagnose children with attention-deficit hyperactivity disorder).

Despite this difference in activity focus, the two disciplines (computer-human interaction and ergonomics) have a common purpose: to integrate users in the design of applications combining BCI and VE for adapting the artefact to its users. To do that, the ISO 9241-210 standard formalised a human-centred design process in four iterative phases:

- Understand and specify the context of use,
- Specify the user needs and the other stakeholders' requirements,
- Produce design solutions (e.g. scenario, mock-up, prototype),
- Evaluate the solutions at all stages in the project from early concept design to long term use to specify design choices.

This model presents a major advantage compared to the participatory design model, because it is formalised and composed of phases. Thereby it can be used to guide designers toward an anthropocentric design. These phases are general and can be adapted by all disciplines interested in the design and evaluation of applications combining BCI and VE. In ergonomics, some methods are used to implement the user-centred design. In the next section, these methods and their benefits from focusing on three phases for which ergonomics are equipped are identified. Indeed, the step "produce design solutions" (step 3) corresponds to the implementation which involves disciplines such as computer science, signal processing and electronics, but not ergonomics (Figure 2).

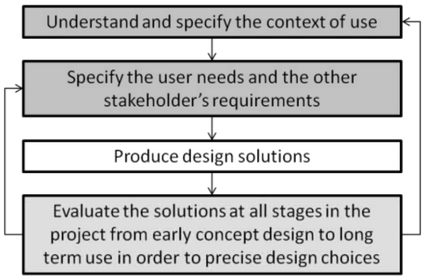

Figure 2. Phases of user-centred design process.

4. Ergonomics methods

We emphasise that the combination of ergonomics methods produces complementary data enriching each of the three phases of user-centred design: specify the context of use (step 1) and the functionalities of the future system (step 2) and evaluate the solutions (step 4). Defining the future context of use and specifying the functionalities of the application combining BCI and VE are closely linked because these two steps involve identification of existing and latent needs. That is why these two steps are assembled in section (4.1). Evaluating solutions at all stages in the project from early concept design to long term use to specify design choices implies the use of evaluation methods of prototypes (4.2) and analysis methods of system appropriation (4.3).

4.1 Ergonomics methods to identify existing needs and latent needs in order to specify the future context of use and the functionalities of the system

Ergonomics uses methods which allow the understanding of the future context of use on the one hand, and the identification of existing needs and promotion of imagination and anticipation of latent needs in order to specify functionalities of the system on the other hand. The existing needs correspond to:

- "Conscious" needs [44]: i.e., those clearly formulated by the (future) end-users,
- "Unconscious" needs [44]: i.e., those which exist but are not clearly formulated by users, because users are not aware of the potential of the chosen technology. This prevents the matching of these potentials with the characteristics of the activity in which the application combining BCI and VE will be integrated.

The "latent" needs [45] are characterized by their nature not yet proven or "undreamed" [44]. These needs are an important issue for emerging technologies, like applications combining BCI and VE, which are still in development in laboratories and whose uses are still sought.

4.1.1 Identification methods of existing needs

In ergonomics, interviews and observations are two methods currently used or recommended for the identification of relevant needs for the design of emerging technologies aiming to assist a specific activity (*e.g.*, a tool for help the decision making in products design). The following studies show that these two methods can be used jointly because interviews and observations produce complementary data. Their use, empirically demonstrated in a highly innovative context (*e.g.*, augmented reality), is encouraging. This suggests that these methods can be used in the design of applications combining BCI and VE dedicated to assist an existing activity.

In a study to identify the needs for the design of a system based on an emerging technology (*i.e.*, augmented reality) to assist the training of automobile mechanics, [38] has conducted semi-directive interviews with 11 mechanics and 33 trainers. She has identified the elements of the mechanics' activity (*e.g.*, breakdowns easy to repair, breakdowns difficult to repair, procedures for resolving breakdowns) and of trainers' activity (*e.g.*, difficulties in preparing courses, difficulties in animating courses, educational resources used). In summary, the interviews raised the conscious needs, i.e. the expectations, the difficulties and the deficiencies to be palliated in the existing situation without the tool.

In another study, Anastassova et al. made observations of seven training sessions in order to describe the use of educational resources by the trainer and to make assumptions about the usefulness of an augmented reality didactic tool. Observations have identified existing but unconscious needs. Indeed, the systematic analysis of activity highlights difficulties and deficiencies in the existing situation but trainers had no conscience of or were unable to verbalise these elements [46].

The collected data from interviews and observations may be formalised in models of activity or models of task [47]. These formalisations provide an opportunity to materialise detailed understanding of user tasks (task order, frequency, difficulty ...), of their environment and their constraints. These models are also a way to move gradually from an activity analysis to a specification of needs in terms of functionalities.

4.1.2 Anticipation methods of latent needs

Anticipating latent needs (*i.e.*, not "existing" for users at a specific moment) involves the use of creativity methods (*e.g.*, Focus Group) to open the field of the potential uses, the functionalities and properties of the artefact [48]. Indeed, [49] showed that Focus Groups promoted the production of innovative concepts (*i.e.*, latent needs) by designers and / or users. Participants are in a creative atmosphere that the authors explain by:

- The opportunity to share experiences, opinions and ideas that can lead to a deeper immersion in the design problem,
- An informal and friendly environment that enhances the trust between users and designers.

This creative atmosphere allows participants to imagine new uses which were not directly deduced from the needs identified by each user [50]. This method is particularly relevant for the design of all emerging technologies, specifically those designed for different users' profile like the BCI-based video game.

This method has recently been used for the design of BCI applications in a study conducted by [11]. The purpose was to determine the barriers and mediators of BCI acceptance in a population with amyotrophic lateral sclerosis. The authors conducted a focus group which involved eight individuals with amyotrophic lateral sclerosis (having previously used a P300-based speller with a visual display) and their nine carers. The focus group consisted of open-ended questions asking participants' impressions of desires and concerns about BCI. It was transcribed in full and data was thematically analysed. Focus group analysis yielded two categories of mediators and barriers to user acceptance of this technology: personal factors (*i.e.*, physical, physiological and psychological concerns) and relational factors (*i.e.*, corporeal, technological and social relations with the BCI). This study shows that a focus group is a relevant method to elicit needs in terms of mediators and barriers concerning the use of BCI by people with amyotrophic lateral sclerosis. This result is encouraging for the use of a focus group to anticipate latent needs of potential users of applications combining BCI and VE. In addition to these methods, ergonomics uses and recommends methods to accomplish the fourth phase of the user-centred design process which corresponds to the evaluation of prototypes (4.2) and the appropriation of the artefact by users (4.3).

4.2 Evaluation methods of prototypes

Traditionally, emerging technologies-based prototypes are supports for people without technical knowledge (*e.g.*, ergonomists, users) to understand technological concepts [51]. Prototypes are also a means to immerse users in the context in which the artefact will be integrated. Users are able to evoke functionalities which were previously latent and unconscious [45]. During the design process, they match their needs and characteristics with the artifact [52]. A simulation of the future situation is an opportunity for the designer to explore the real impact of the artifact on the users' activities. This simulation allows them to identify the improvements to be implemented so that the users have a real benefit from its use [53].

In a user-centred design of applications combining BCI and VE, prototypes are evaluated through user-based testing (*i.e.*, simulation to study the users' behaviour in front of the application) followed by questionnaires. This observation is illustrated with three studies detailed below. These studies provide an overview of the way the evaluation is carried out in the field of BCI and VE on three aspects: the number of participants, the location of the test and the evaluation objectives (objective evaluation of performance, subjective evaluation etc).

To identify the improvements to make to their application and the feedback from the navigation experience, [54] evaluated a BCI used for controlling a robot called "NXT robot" with 54 participants at a national technology exhibition centre for three days. The task was to move the robot forwards, to accelerate and stop it before the end of a track. The questionnaire contained general comments and 7-point Likert scale for measuring the ability to control, the application responsiveness to actions initiated the effectiveness of the user interactions with the robot, in what way the control mechanism of the robot was natural and how the sense of moving the robot was compelling.

[24] conducted a study aiming to explore the synergies of a hybrid BCI and a VR-based neurorehabilitation system. This study involves 18 participants and consisted of four phases. First, the BCI classifier was trained. Then, the "Spheroids" calibration phase was used to assess the level of control of the participants by asking them to drive the virtual arms to specific locations. Subsequently, participants played the "Spheroids" training game. Finally, all participants answered a 5-point Likert scale (1 lowest, 5 highest) of 23 questions covering different aspects: enjoyment of the experience, perceived performance learning during task execution, level of task ease, level of control of the virtual avatar, and appropriateness of the system configuration (for instance, if arms were too fast or too slow).

[9] have recently elaborated a standardised questionnaire, inspired by the Game Experience Questionnaire and Engagement Questionnaire. This questionnaire can be used to evaluate the user experience in a BCI-based interaction for entertainment purposes. It offers optional items depending on the category of BCI (*e.g.*, passive BCI, active BCI). For passive BCI, items are the degree of comfort and of

distraction from the main task of the BCI hardware. For active BCI, items concern applicability of the mental tasks and perceived speed of the BCI on the users’ actions.

These studies show three elements. First, applications combining BCI and VE, even relatively immature, can be evaluated with a large number of users with highly varying skills and potentially very heterogeneous needs. This is a key element in the context of BCI-based games which must be adapted to users other than those who have been involved in the design. Second, these studies indicate diversity in the implementation of user based testing that can take place in laboratory conditions (i.e., controlled situations) and in conditions similar to real situations of interaction (typically, playing video games at home where the variables are not controlled). This suggests that user-centred evaluations of applications combining BCI and VE can take place under experimental conditions (in the laboratory) and in more ecological conditions relative to the future situation of use. These two ergonomic approaches are complementary and coexist for the design of these emerging technologies. This opens perspectives for evaluation with users of applications combining BCI and VE for several types of applications (*e.g.*, medical diagnostic tools, video games). Third, it provides information on the questions contained in the questionnaire to assess the application combining BCI and VE: these questions are generally Likert scales (5 or 7-point) and less frequently open-ended questions that allow the questioned person to express them freely. The items covered in these questionnaires concern the system (*e.g.*, appropriateness of the system configuration, application responsiveness to initiated actions) and subjective elements perceived by the user (*e.g.*, enjoyment of the experience, level of task ease).

4.3 Analysis methods of system appropriation

To study system appropriation, longitudinal studies are used. They are usually implemented through observations, interviews and self-confrontation made at different periods (*e.g.*, at 0 month, 3 months and 6 months after the integration of artefact in a situation). This allows the ergonomist to analyse the strategies and identify the difficulties encountered by users in real use. For example, [55] - by observation - showed that users do not use all the implemented features (*e.g.*, space for dialogue) and that they developed new rules through the use of the tool (*e.g.*, abbreviations). In addition, these longitudinal studies allow us to help users in their evolution and to train them to use this new tool. For example, software designers in a users’ company can conduct regular training sessions and can suggest the use of software for several months to facilitate progressive learning of this artefact by the users [56]. It also allows designers to finalise the application based on the daily feedback of the users [56].

Longitudinal studies have been conducted in the context of BCI to measure the influence of psychological state and motivation on the BCI performance of patients with amyotrophic lateral sclerosis (*e.g.*, [57]). In this study, six participants were trained for several months either with a BCI based on sensorimotor rhythms or with a BCI based on event-related potentials (*i.e.*, P300), or both. Questionnaires assessing quality of life, severity of depressive symptoms, mood and motivation were filled out by the participant before each training session. The results suggest that P300-based BCI must be a first choice for allowing severely paralysed patients to control a communication program based on a binary spelling system. The results also suggest that motivational factors may be related to the BCI performance of individual subjects and suggest that motivational factors and well-being should be assessed in standard BCI protocols.

This study illustrates that longitudinal studies have been conducted to measure the evolution of some parameters' effects on the use of a BCI-based speller and thus to study the appropriation of the BCI by users. This is necessary because the lack of training on these new tools and the lack of support are factors that may lead the end users to abandon their use

The methods described in this section are used, in ergonomics, to design BCI-based VR applications suited for end-users (Table 3).

Table 3. Decomposition of ergonomics methods (second row) that can be used in different phases of a user-centred design process (first row) for applications combining BCI and VE.

Phases of user-centred design process	Methods
Understand and specify the context of use, Specify the user needs and the other stakeholder's requirements	Identification methods of existing needs (Interviews, Observations)
	Anticipation methods of latent needs (Focus Group)
Produce design solutions	
Evaluate the solutions at all stages in the project from early concept design to long term use in order to precise design choices	Evaluation methods of prototypes (User based tests, Questionnaires)
	Analysis methods of system appropriation (Longitudinal studies)

These methods can be used to design and evaluate usefulness, usability, acceptability, hedonic quality, sense of presence, immersion and user experience. In the next section, the way in which these ergonomic criteria can be taken account in the context of an application combining BCI and VE are presented.

5. Ergonomics criteria

According to a recent review conducted by [58], designing a system suited for end-users implies the system has good instrumental (usefulness, usability) and non-instrumental qualities (acceptability, hedonic quality, appealingness, immersion, presence), and generates a positive user experience. In the following section, these three factors based on ergonomic criteria were defined.

5.1 Instrumental qualities

The instrumental qualities correspond to the two most common ergonomic criteria in the literature: usefulness and usability.

5.1.1 Usefulness

In ergonomics, the term "usefulness" oscillates between two meanings: *purpose-usefulness* and *value*-usefulness [59].

Purpose-usefulness is the description of system features and its uses. This description can take many forms depending on the phase of the design process (concept, specification, use requirement, mock-up, prototype, final artefact). Purpose-usefulness corresponds to the functionalities of an artefact. These features are determined at a given time, even if they can be subsequently modified by users. In the field of BCI, the study conducted by [11] aims at collecting the user needs of people with amyotrophic lateral sclerosis in relation to a BCI speller, using a focus group.

Value-usefulness is defined as a significant advantage of the artefact for users in activities mediated by a computer system; this advantage is always relative to: the objectives of the user, the existing tools, the use environment and the dependencies on other activities [60]. Value-usefulness refers to improvements and benefits that the artefact provides to the users. In the field of emerging technologies in general and BCI in particular, these benefits are evaluated in the short, medium or long term. For example, [29] conducted a study to evaluate the usefulness of their virtual reality – neuro-feedback system for treating children with Attention Deficit Hyperactivity Disorder (ADHD). In other words, they wanted to show that the virtual reality neuro-feedback training could improve sustained attention. This study involves 12 subjects with ADHD aged form 8 to 12 years old, who were trained at least twice per week with five virtual environment games for 25-35 minutes. During the training period, all subjects were requested to stop taking any medication and behavioural therapy. To measure children' s attention, authors used the integrated visual auditory – continuous performance test[5] (IVA-CPT) at the beginning of treatment and after each twenty training sessions. Results show that the attention of subjects had been strengthened after 20 training sessions.

The usefulness of applications combining BCI and VE has been the subject of only one study. This study aimed to measure the benefits of a BCI and VE based system (*e.g.* increase the level of attention in ADHD children) with methods and metrics specific to the application of why the system was / is / will be designed. The examples on the definition and evaluation of the usefulness are in the field of health (disability and therapy). Research on this criterion remains to be carried out especially in areas where a component of these systems (*i.e.,* virtual reality) is already recognised as beneficial (*e.g.,* learning).

5.1.2 Usability

In 1998, the International Organization for Standards published a definition of usability (ISO 9241-11): "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" . Some authors [61] add learnability and memorability to define usability.

Usability is, therefore, a combination of five elements: effectiveness, efficiency, satisfaction, learnability and memorability [62]:

[5] http://www.braintrain.com/ivaplus/

- Effectiveness concerns the fact that the software allows the user to achieve the specified goal,
- Efficiency is the capacity to achieve a task with the minimum of resources for user (*i.e.*, the effort),
- Satisfaction is influenced by ease to use and by non-instrumental qualities (*e.g.*, aesthetics aspects),
- Learnability is what allows a novice user to devote himself quickly to a task, reducing the time needed to learn the application. The second aspect of learnability is to train the user to reliably perform mental tasks [14],
- Memorability is what allows the user to perform the tasks after a period of non-use without having to re-learn the functioning of the application.

Usability of BCI application has already been evaluated in some studies. For example, [10] conducted a study to evaluate the usability of two BCI devices: Emotiv EPOC and the Neurosky MindWave. Authors compared user comfort, experiment preparation time (*i.e.*, total time from initial placement to final adjustment), signal reliability and ease of use of each BCI. This study involves 13 participants. Each participant completed a training phase before playing several simple games included with each system like Pong, Tetris, and SpadeA. After having worn the BCI device for 15 minutes, the participant completed a post-experiment questionnaire. Results show that the preparation time for the Emotiv EPOC is longer than for the Neurosky MindWave and that the majority of participants indicate that the Emotiv EPOC is comfortable whereas the Neurosky MindWave is not. Moreover, the MindWave allows an easier signal acquisition and that the EPOC clearly has contact issues due to participants' hair. However, the signal is maintained and even improved during the session once the EPOC is connected and calibrated, while the MindWave experiences more signal fluctuations.

This study describes the evaluation of a BCI device. However, others studies concern the usability evaluation of BCI-based interaction with another system (*e.g.,* robot). [63, 64] aimed to evaluate a new brain-actuated wheelchair concept that relies on a synchronous P300 brain-computer interface integrated with an autonomous navigation system, while [65] conducted an evaluation of an EEG (P300) based human between remote places via internet, using only brain activity. In each of these studies, the evaluation concerns the effectiveness and the efficiency of the BCI-based interaction and of the graphical interface.

These studies suggest that the usability evaluation of applications combining BCI and VE can have different objectives. Indeed, it can concern either the BCI device, or the BCI-based interaction with another output device like a robot.

5.2 Non instrumental qualities

5.2.1 Acceptability

According to [66, 67], acceptability refers to an individual's perception of the system's value. To assess the acceptability, authors try to identify the intentions of individuals to use a system through questions. Thus, models of acceptability identify the variables that contribute significantly to the determination of intentions to use a technology. Among these models, the most complete is the UTAUT (Unified Theory of Acceptance and Use of Technology) by [68]. According to this model, behavioural intention is influenced by the performance expectancy, effort expectancy and social influence, use behaviour is influenced by behavioural intention and facilitating conditions. Previous experience with the system, the voluntariness or not of use, gender and age moderate the effects of direct determinants like performance expectancy, effort expectancy, social influence and facilitating conditions.

5.2.2. Hedonic qualities and appealingness

Non-instrumental qualities have only recently been integrated into ergonomic analysis [58, 69]. These non-instrumental qualities correspond to the "hedonic quality" and the "appealingness". Indeed, the hedonic quality refers to the aspects of an artefact that are related in particular to a person's pleasure [70]. The pleasure derived from the use of an artefact is associated with its appealing characteristics and aesthetic to the pleasure perceived during interaction [71]. To the authors' best knowledge, there are no studies on the pleasure perceived by a user during a BCI-based interaction. Therefore, these non-instrumental qualities have been the object of several studies in the field of others products. For example, [71] conducted four studies in order to develop a measurement instrument of aesthetic characteristics of web sites. These studies indicate that it is relevant to evaluate the hedonic quality of a software product (i.e., website or application combining BCI and VE).

5.2.3. Immersion and Presence

In virtual reality, two additional dimensions can be specified: immersion and presence. Each of these dimensions has led to many definitions (e.g., [72, 73]). We retain the following definition for immersion: this dimension corresponds to the degree with which the system interface controls the sensory inputs for each modality of perception and action [74]. So, immersion can be described (but not only) in terms of specific devices: a common dichotomy derives from the opposition of "immersive" systems (Head Mounted Display, Cave Automatic Virtual Environment) and "non immersive" systems (desktop, mouse).

According to [72], immersion determines the sense of presence perceived by users. The International Society for Presence Research (2000) ruled that presence is "a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience". In others words, the sense of presence is the experience of being inside a VE, being in a normal state of consciousness [73].

These links between immersion and presence appeared in the literature: immersion has been studied in the context of many studies on BCI and VE. For example, [75] showed that an immersive environment can improve the sense of presence while carrying out navigational tasks through imaginary movements. [76] observed that P300 can be used successfully in immersive virtual environments and [77] proved that P300 based navigation lowered the sense of presence compared to gaze-based navigation. In the field of BCI, this dimension was evaluated in some studies. For example, [78] conducted a study with 17 participants aiming to measure immersion in a BCI Game named "Mind the Sheep!". Their experiment consisted of two different sessions: a BCI session and a non-BCI session. Each session was divided into three trials: a familiarity trial (i.e., participants had to collect 10 objects which were placed across the playground), an easy trial (i.e., participants had to park a small flock of 5 sheep using the dogs) and a difficult trial (i.e., participants had to gather 10 sheep, which were more scattered across the playground, into one pen that was placed in the centre of the playground). After each session participants filled in a questionnaire on their perceived immersion in the game. The 31 questions dealt with cognitive involvement, emotional involvement, real world dissociation, challenge and control). Results showed that the BCI selection method was more immersive than the non-BCI selection method (i.e., mouse).

5.3. User experience

User experience is a consequence of an interaction between a user (with his characteristics) and a product (with its features and qualities) appearing after an evaluation process [79]. [80] proposed a model *(called the CUE-Model)* that incorporates most of the components which are evident in many approaches of the user experience (par ex., [79, 81]). According to the author, the user experience has three dimensions: the perceived instrumental qualities, the perceived non instrumental qualities and the emotional reactions influenced by these perceptions. In other words, the user experience is defined by the perceived usefulness and usability (*i.e.,* instrumental qualities), by the perceived hedonic quality, appealingness and the sense of presence (*i.e.,* non-instrumental qualities) and by the emotional reactions which arise from subjective feelings, physiological reactions, motor expressions and cognitive appraisals [82, 83].

This dimension has been evaluated particularly in the context of BCI-based video games. The user experience resulting from these technologies has been measured by its perceived usability, its hedonic quality, its appealingness and the sense of presence. Some studies on user experience in BCI and video games are mentioned below.

A first example is the study conducted by [14] aiming to find the differences between real and imagined movement in a BCI game in relation to user experience and performance. The BCI was used to interact with a game called BrainBasher (the goal of this game is to perform specific brain actions as quickly as possible; for each correct and detected action the user scores a point). Twenty people participated to this study. After the game session, the participant filled out a user experience questionnaire, based on the Game Experience Questionnaire [84]. Results showed that there were differences between actual and imagined movement in BCI gaming in user experience and in performance. Real movement produced a more reliable signal and the user stays more alert, while the imagined movement is more challenging.

A second example is the study conducted by [85] aiming to find the differences between real and imagined movement as modalities in a BCI game. The BCI game used for this research was BrainBasher. Twenty people participated to this study. Results showed that there are significant differences in user experience and that actual movement was a more robust way to communicate through a BCI.

A third example is user experience evaluations on a game, conducted by [13]. The purpose was e.g. to compare the user experience resulting from the use of different controllers (*e.g.,* BCI, mouse) and to understand the added-value relating exclusively to BCI control. In order to do that, the author proposed a method called "equalised comparative evaluation" to compare two or more controllers independently of their performances.

These studies are focused on the comparison of user experience according to paradigms and interaction devices, only in the game field. So, user experience was evaluated with a specific questionnaire on game experience. An interesting perspective would therefore be to analyse the user experience of applications combining BCI and VE in fields other than videogame.

To design a BCI-based VR application suited for end-users, all these criteria (Table 4) must be evaluated with specific metrics.

Table 4. Ergonomic criteria can be used in phases of user-centred design process for applications combining BCI and VE.

Phases of user-centred design process	Methods	Ergonomic criteria
Understand and specify the context of use, Specify the user needs and the other stakeholder' s requirements	Identification methods of existing needs (Interviews, Observations)	Usefulness Usability Acceptability
	Anticipation methods of latent needs (Focus Group)	
Produce design solutions		
Evaluate the solutions at all stages in the project from early concept design to long term use in order to precise design choices	Evaluation methods of prototypes (User based tests, Questionnaires)	Usefulness Usability Acceptability Hedonic qualities Appealingness Immersion and presence Emotions User experience
	Analysis methods of system appropriation (Longitudinal studies)	

In the next section, these indicators are identified.

6. Metrics

To assess conformity of BCI-based VR applications with each ergonomic criterion, metrics on the basis of literature are described.

6.1. Metrics used to assess usability

Usability of applications combining BCI and VE is the criteria the most evaluated compared to the others. The BCI-based interaction is evaluated in term of effectiveness and efficiency using, for example [63, 65]:

- The degree of accomplishment of the task,
- The distance travelled to accomplish the task,
- The task success (*i.e.*, number of collisions),

- The total time taken to accomplish the task (in seconds),
- The number of missions to complete the task,
- The real BCI accuracy (*i.e.,* BCI recognition rate),
- The useful BCI accuracy (*i.e.,* ratio of good selections plus useful errors per total number of selections),
- The total BCI errors (*i.e.,* number of incorrect selections),
- The useful BCI errors (*i.e.,* incorrect selections that were reused to accomplish the task),
- The useful BCI accuracy (*i.e.,* correct selections plus useful errors versus total).

To evaluate the effectiveness and the efficiency of the graphical interface, the following criteria were used by [65]:

- The usability rate (*i.e.*, number of selections per mission, the number of missions per minute),
- The command utility (*i.e.*, command usage frequency),
- The number of errors by misunderstanding in the interface and the number of far goals and turns in the navigation mode.

To evaluate the satisfaction of an application combining BCI and VE, the semantic differential scales (Table 5) corresponding to the following items provided by [86] can be used: Understandable *versus* Incomprehensible, Supporting *versus* Obstructing, Simple *versus* Complex, Predictable *versus* Unpredictable, Clear *versus* Confusing, Trustworthy *versus* Shady, Controllable *versus* Uncontrollable and Familiar *versus* Strange.

Table 5. Example of semantic differential.

	1	2	3	4	5	6	7	
Incomprehensible	○	○	○	○	○	○	○	**Understandable**

To the authors' best knowledge, there are no studies on the evaluation of learnability and memorability in the BCI field. But, in technological systems, learnability is assessed by comparing the time of task execution by a novice group (who never uses the application) and the time of task execution by an expert group (who already uses the application). If the time taken by the group of novices is inferior or equal to the time taken by the experts group, then the learnability of application is good. Memorability is assessed by measuring the time of task execution at different times over a period of weeks. If the time obtained during the first week is superior or equal to the time obtained during the following weeks, then the memorability of application is good.

6.2. Metrics used to assess usefulness

Several metrics can be used to assess the system's usefulness. A well-known metric, and common to all emerging systems, is the adequacies *versus* inadequacies between the features implemented in a system on the one hand, and those desired at a time T by the user on the other hand [87]. These adequacies or inadequacies are collected with the number of responses Yes *versus* No to the question: Do you think this functionality / information is useful? They are collected with metrics resulting from requirement prioritization: nominal scale, ordinal scale, ratio scale methods [88]. In nominal scale methods, requirements are assigned to different priority groups. An example is the MoScoW method, which consists of grouping all requirements into four priority groups, being the requirements that the project (must / should / could / won’ t) have. All requirements listed in a category are of equal priority, not allowing a finer prioritization. Ordinal scales methods produce an ordered list of requirements; for example, the simple ranking where the most important requirement is ranked ‘one’ and the least important is ranked ‘n’ . Another known method called Analytic Hierarchy Process asks users to compare all pairs of requirements. Ratio scale methods provide the relative difference between requirements (*e.g.*, the hundred dollar method asks users to allocate a sum of money to each requirement). In addition to an ordered list of requirements, this method also helps us to discover the relative importance of each requirement in relation to the others.

Other metrics allow us to evaluate benefits and advantages for the user in relation to his goals, existing tools, the environment of use and dependencies with other activities. These metrics are more specific to the domain for which the application was designed. To make this clearer, let us take some examples of the fields in which applications combining BCI and VE are used. To evaluate the usefulness of a system to support learning, the metrics are specific to the knowledge that the system (overall) allows for learning. To evaluate the usefulness of their virtual reality neuro-feedback system for treating children with attention deficit hyperactivity disorder [29] used two major quotients from the Integrated Visual Auditory Continuous Performance Test:

- Reponse Control Quotient measured with three scales: Prudence, Consistency, Stamina,
- Attention Quotient measured with three scales: Vigilance, Focus and Speed.

As an example, for a BCI-based speller, these benefits can be measured using the indicator of well-being (*i.e.,* the quality of life and level of anxiety). Indeed, the quality of life increases while the level of anxiety decreases progressively during the use of an application which allows people who cannot communicate through speech to “speak” .

6.3. Metrics used to assess acceptability

According to [68], acceptability is measured by eight factors:

- Performance expectancy is defined as the degree to which an individual believes that using the system will allow him/her to gain in job performance,
- Effort expectancy corresponds to the degree of ease associated with the use of system,
- Attitude toward using technology corresponds to an individual’ s overall affective think this should be effective reaction to using a system,
- Social influence is defined as the degree to which an individual perceives that important others believe he/she should use the new system,
- Facilitating conditions are defined as the degree to which an individual believes that an organizational and technical infrastructure exists to support use of the system,
- Self-efficacy corresponds to "an individual’ s belief in one’ s capability to organise and execute the courses of action required to produce given attainments” ,
- Behavioural intention to use the system corresponds to the intention to use the system in the next months,

- Anxiety.

In the Table 6, metrics (or items) suggested by [68] are described:

Table 6. Items used to assess factors influencing acceptability.

Factors influencing acceptability	Items
Performance expectancy (for that "performance expectancy" is evaluated, it is necessary that the system combining BCI and VE has been designed to satisfy an actual and concrete application)	I would find the system useful in my job Using the system enables me to accomplish tasks more quickly Using the system increases my productivity If I use the system, I will increase my chances of getting a raise
Effort expectancy	My interaction with the system would be clear and understandable It would be easy for me to become skilful at using the system I would find the system easy to use Learning to operate the system is easy for me
Attitude toward using technology	Using the system is a good idea The system makes work more interesting Working with the system is fun I like working with the system
Social influence	People who influence my behaviour think that I should use the system People who are important to me think that I should use the system The senior management of this business has been helpful in the use of the system In general, the organization has supported the use of the system
Facilitating conditions	I have the resources necessary to use the system I have the knowledge necessary to use the system The system is not compatible with other systems I use A specific person (or group) is available for assistance with system difficulties
Self-efficacy	If there was no one around to tell me what to do I go If I could call someone for help if I got stuck If I had a lot of time to complete the job for which the software was provided

	If I had just the built-in help facility for assistance
Behavioural intention to use the system	I intend to use the system in the next <n> months I predict I would use the system in the next <n> months I plan to use the system in the next <n> months
Anxiety	I feel apprehensive about using the system It scares me to think that I could lose a lot of information using the system by hitting the wrong key I hesitate to use the system for fear of making mistakes I cannot correct The system is somewhat intimidating to me

These items formalised in the form of positive affirmation are associated with the Likert scale on which the user notes the degree of agreement or disagreement (Table 7):

Table 7. Likert scale associated to an item of "effort expectancy".

Learning to operate the system is easy for me:								
	1	**2**	**3**	**4**	**5**	**6**	**7**	
Strongly disagree	○	○	○	○	○	○	○	**Strongly agree**

6.4. Metrics used to assess hedonic quality and appealingness

To evaluate the hedonic quality of all technological systems, [86] suggested the following items using the semantic differential scales: Interesting *versus* Boring, Costly *versus* Cheap, Exciting *versus* Dull, Exclusive *versus* Standard, Impressive *versus* Nondescript, Original *versus* Ordinary, and Innovative *versus* Conservative. To evaluate the comfort and discomfort of BCI devices, [10] evaluated the comfort through three indicators: the comfort of the device (very uncomfortable, uncomfortable, indifferent, comfortable and very comfortable), the time the participants felt they could comfortably wear the device (0–5 minutes, 5–20 minutes, 20–60 minutes, 60–120 minutes and more than 120 minutes) and the type of discomfort perceived (sharp, dull, itchy, heavy, throbbing, awkward, burning or other).

To evaluate the appealingness of these systems, [86] suggested the following items: Pleasant *versus* Unpleasant, Good *versus* Bad, Aesthetic *versus* Unaesthetic, Inviting *versus* Rejecting, Attractive *versus* Unattractive, Sympathetic *versus* Unsympathetic, Motivating *versus* Discouraging and Desirable *versus* Undesirable.

6.5. Metrics used to assess immersion and presence

To measure immersion and presence during an interaction with a VE, [72] designed a questionnaire which was used in numerous studies [89]. In their approach, these authors evaluate the presence according to four categories:

- The control factors correspond to the degree of control that a person has in interacting with the VE, the immediacy of control (*i.e.*, delays between the action and the result), the anticipation concerning what will happen next, whether or not it is under personal control, the mode of control (*i.e.*, the manner in which one interacts with the environment is a natural or well-practiced method) and the physical environmental modifiability (*i.e.*, ability to modify physical objects in an environment)
- The sensory factors are the sensory modality (*i.e.*, visual information and other sensory channels), the environmental richness in term of information, the multimodal presentation to stimulate completely and coherently all the senses, the consistency of multimodal information, the degree of movement perception (*i.e.*, the observer must perceive self-movement through the VE) and the active search (*e.g.*, the observers can modify their viewpoint to change what they see),
- The distraction factors correspond to the isolation from devices (*e.g.*, head-mounted display), the selective attention (*i.e.*, the observer's willingness or ability to focus on the VE stimuli and to ignore distractions) and the interface awareness,
- Realism factors are the scene realism governed by scene content, texture, resolution, light sources, field of view and dimensionality, the consistency of information with the objective world, the meaningfulness of experience for the person and the anxiety/disorientation when users return from the VE to the real world.

In the Table 8, you find metrics (or items) suggested by [72]:

Table 8. Items used to assess factors influencing immersion and presence.

Factors influencing immersion and presence	**Items**
Control factors	– How much were you able to control events? – How responsive was the environment to actions that you initiated (or performed)? – How natural did your interactions with the environment seem? – How natural was the mechanism which controlled movement through the environment? – Were you able to anticipate what would happen next in response to the actions that you performed? – How well could you move or manipulate objects in the virtual environment? – How much delay did you experience between your actions and expected outcomes? – How quickly did you adjust to the virtual environment

	experience? – How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? – How much did the control devices interfere with the performance of assigned tasks or with other activities?
Sensory factors	– How much did the visual aspects of the environment involve you? – How much did the auditory aspects of the environment involve you? – How compelling was your sense of objects moving through space? – How completely were you able to actively survey or search the environment using vision? – How well could you identify sounds? – How well could you localize sounds? – How well could you actively survey or search the virtual environment using touch? – How compelling was your sense of moving around inside the virtual environment? – How closely were you able to examine objects? – How well could you examine objects from multiple viewpoints?
Distraction factors	– How much did the visual display quality interfere or distract you from performing assigned tasks or required activities? – How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
Realism factors	– How much did your experiences in the virtual environment seem consistent with your real-world experiences?

These items formalised in the form of questions are associated with the Likert scale on which the user notes his/her subjective experience (Table 9):

Table 9. Likert scale associated to an item of "sensory factors".

How compelling was your sense of moving around inside the virtual environment?								
	1	**2**	**3**	**4**	**5**	**6**	**7**	
Not compelling	○	○	○	○	○	○	○	**Very compelling**

6.6. Metrics used to assess emotion

The user experience is a consequence of usability, utility, hedonic qualities, appealingness, the sense of presence and the resulting emotions. Now, we focus on emotions. In the models re-used in ergonomic literature (*e.g.,* [82]), emotions are measured with several indicator categories:

- Subjective feelings evaluated and measured by the "Self-Assessment Manikin" defined as "a non-verbal pictorial assessment technique that measures the pleasure, arousal, and dominance associated with a person's affective reaction to a wide variety of stimuli" [90]. Pleasure is measured by the following items: Unhappy *versus* Happy, Annoyed *versus* Pleased, Unsatisfied *versus* Satisfied, Melancholic *versus* Contented, Despairing *versus* Hopeful and Bored *versus* Relaxed. Arousal is measured with these adjectives: Relaxed *versus* Stimulated, Calm *versus* Excited, Sluggish *versus* Frenzied, Dull *versus* Jittery, Sleepy *versus* Wideawake and Unaroused *versus* Aroused. Dominance is measured with items: Controlled *versus* Controlling, Influenced *versus* Influential, Cared for *versus* In control, Awed *versus* Important, Submissive *versus* Dominant and Guided *versus* Autonomous.
- Physiological reactions measured for instance by heart rate and electro dermal activity,
- Motor expressions measured with electromyography of the two facial muscles associated with positive emotions (*zygomaticus major*) and negative emotions (*corrugator supercili*),
- Cognitive appraisals measured by the "Geneva Appraisal Questionnaire" [6] which measures, according to [91], five appraisal dimensions: intrinsic pleasantness (*i.e.*, a stimulus event is likely to result in a positive or negative emotion), novelty (*i.e.*, measure of familiarity and predictability of the occurrence of a stimulus), goal/need conductiveness (*i.e.*, importance of a stimulus for the current goals or needs), coping potential (*i.e.*, extent to which an event can be controlled or influenced), and norm/self-compatibility (*i.e.*, extent a stimulus satisfies external and internal standards).

7. Discussion

The studies concerning the design of user-centric applications combining BCI and VE are uncommon compared to studies aimed to optimise the performance of these applications (*e.g.*, [92, 93, 94]). One possible reason may be that the research on BCI and VE based systems supposes the technological development which is necessary before the end-users are confronted with the system in actual context of use. However, the integration of end-users from the early design phase to the use of application is necessary to design applications which will be suitable. Despite this, very few papers have focused on the methods, criteria and metrics for the ergonomic design of applications combining BCI and VE. Our user-centred methodological framework is, therefore, an original contribution.

[6] http://www.affective-sciences.org/system/files/webpage/GAQ_English.pdf

Concerning the studies on user-centred design, our paper makes three observations. Firstly, the studies concern mainly the evaluation phase dealing with the evaluation of prototypes (*e.g.*, [54, 24]) and appropriateness of applications (*e.g.*, [57]), to the detriment of the early design phase aiming to understand the context of use or to specify the user needs (*e.g.*, [11]). Secondly, the majority of studies use only one method: the user based test is mainly used to evaluate the usability (*e.g.*, [25, 95]) and the usefulness (*e.g.*, [29]; the focus group to characterise the acceptability (e.g., [11] and the questionnaire is used to measure the user experience (*e.g.*, [9] and, in longitudinal studies, to assess the application' s appropriateness (*e.g.*, [57]). Thirdly, the assessments of applications combining BCI and VE focused on a single criterion which was mainly the usability (*e.g.,* [96, 10, 63, 65]) at the expense of other criteria such as immersion , presence (*e.g.*, [78] or usefulness (*e.g.*, [29]).

To overcome these observations, our framework suggests three guidelines. The first guideline insists on all phases of the user-centred design process for which ergonomics is equipped: understand and specify the context of use (phase 1), specify the user needs (phase 2), evaluate the prototypes and assess the appropriateness of applications (phase 4). Indeed, involving end-users from the identification of needs before the implementation of the application to the application' s use allow designers to integrate the evolution of characteristics and needs of users. Our methodological framework is comprehensive in that it deals with every phase of the process, and not only the evaluation phase partially covered in the literature of human-computer interaction. The second guideline concerns the necessity to use several methods: interview, observation and focus group to identify the needs, user based testing and questionnaire to evaluate the systems and longitudinal studies to measure the appropriateness of the system. Indeed, using several ergonomic methods to study a criterion is advisable because they provide complementary data. Our methodological framework suggests implementing at least two methods to evaluate the same criterion. For example, to evaluate the usefulness of an application combining BCI and VE, it is desirable to achieve (1) quasi experimentation-based longitudinal studies (*i.e.*, comparison between a group that uses the application and another group that does not use it, for a period of several months), and (2) after-use questionnaire tests with questions on the intention to use the application in the future etc. The third guideline recommends defining and measuring several ergonomic criteria and underlines the importance of evaluating one criterion using several metrics. Indeed, designing a technological system suited to the end-user implies integrating several criteria and not just one: typically, a usable system cannot be used if it is not useful for its users. Our methodological framework incorporates several ergonomic criteria such as usefulness, usability, acceptability, hedonic qualities, appealingness, immersion and presence, emotions and user experience, and several metrics for each of them.

In accordance with these previous guidelines, the implementation of this methodological framework to design and evaluate numerous applications combining BCI and VE could suggest several research perspectives. A first perspective could be to assess empirically the potential of a user-centred methodological framework, comparing one application combining BCI and VE resulting from a technocentric design process (i.e., as traditionally implemented to develop these applications) and an application resulting from a design process based on our user centred framework. A second perspective could be to improve the framework with the empirical results using it to design applications for different scopes (*e.g.*, applications combining BCI and VE for health, learning). An example of results could be the enhancement of the metrics' database for the usefulness criterion that is highly dependent on the applications' scope. Because one conclusion of the massive use of this framework could be a partial use depending on the application, a third perspective would be to develop a tool to assist in the decision-making concerning the selection of methods, criteria and metrics according to the scope of the application.

8. Conclusion

The literature on BCI and VE suggests that evaluations are mainly technocentric in order to technically improve the applications combining BCI and VE before using them in real contexts of use. However, some recent works tend to show the need to include characteristics, expectations and requirements of end-users in early design phases. To do so, methodological guidelines are necessary. In this paper, a user-centred methodological framework is proposed and defined to guide the design and evaluation of applications combining BCI and VE. This framework is based on literature on ergonomics and human-computer interaction in the context of BCI used in virtual reality and video games.

For each user-centred design phase, our framework has discussed methods, criteria and metrics to guide designers in the design and evaluation of the usefulness, usability, acceptability, hedonic qualities, appealingness, immersion and presence, emotions and more generally user experience associated with applications combining BCI and VE.

It suggested specific methods to be used to define and measure specific criteria. Indeed, it explained that usefulness, usability and acceptability are criteria to be considered both in identifying and anticipating user needs (i.e., contexts of use and features) through interviews, observations and focus group. These criteria have also been integrated in the evaluation phase to assess both intermediate solutions (e.g., prototypes) with user based tests associated with questionnaires, and the system's appropriateness by conducting longitudinal studies. In the same way, it described how hedonic qualities, appealingness, immersion and presence, emotions and more generally user experience are the criteria also to be measured in the evaluation phase through user based tests and questionnaires.

Moreover, this framework recommended specific metrics associated with each ergonomic criterion which can be implemented in the methods. For example, in a questionnaire or in an interview's grid, some questions can allow the evaluation of usability (e.g., degree of complexity), usefulness (*e.g.*, order of priority of the suggested functions), acceptability (*e.g.*, intention to use the system in the next 4 months), hedonic quality (*e.g.,* degree of boredom), appealingness (*e.g.*, degree of appeal), emotion (*e.g.*, degree of arousal), immersion and presence (*e.g.*, the degree of provision of visual aspects).

Finally, this framework is a methodological support to guide the designers of tools combining BCI and VE so that they are adapted to human characteristics, to the users' needs and to the context in which these tools will be integrated.

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